Combination of optical and infrasonic observations applied to the PRISMA fireball network: towards independent estimates of entry energy

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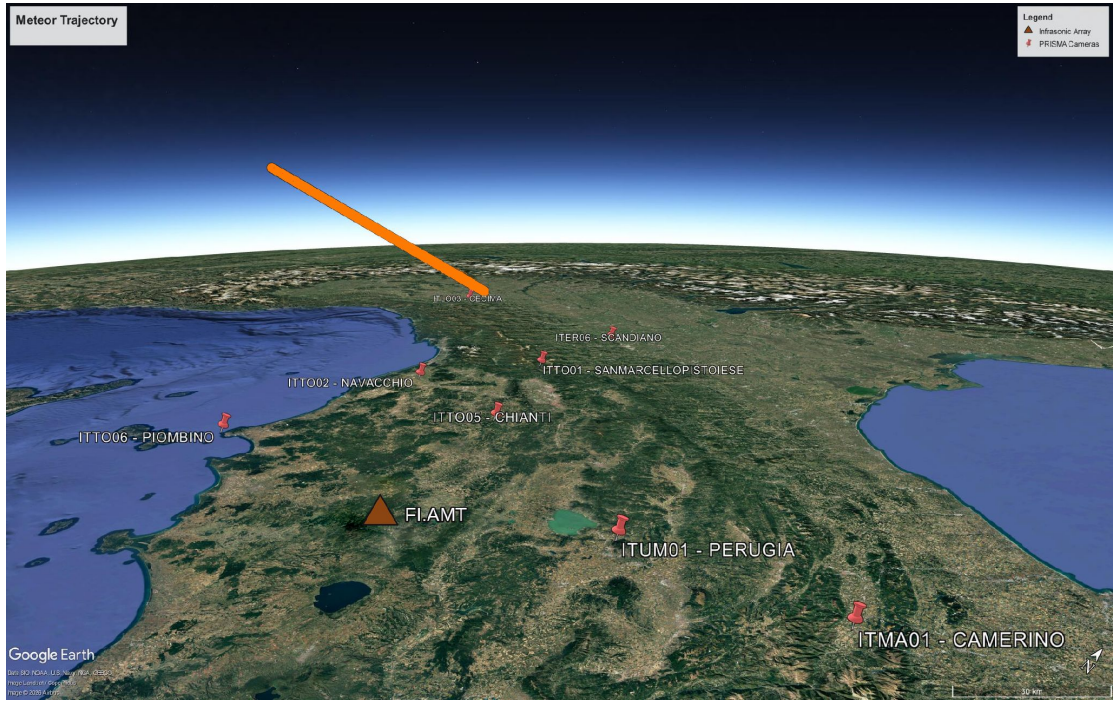
Optical observations of fireballs: trajectory and energy

- Optical networks accurately track the trajectory: position, speed and deceleration
- The energy needs the mass, from the light curve, the deceleration, or both
- From the light curve: the mass depends on the luminous efficiency
- From the deceleration: the mass depends on the shape, drag and density of the body

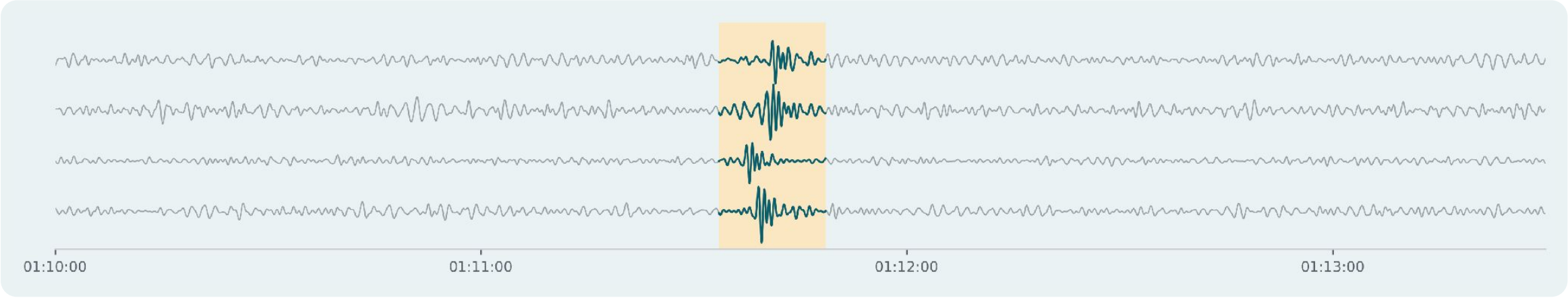


Trajectory of the 2021-10-01 fireball (orange), the PRISMA cameras that recorded it (red) and the FI.AMT infrasound array (brown triangle). Map: Google Earth.

An estimate that uses neither the light nor the deceleration would be an independent check.

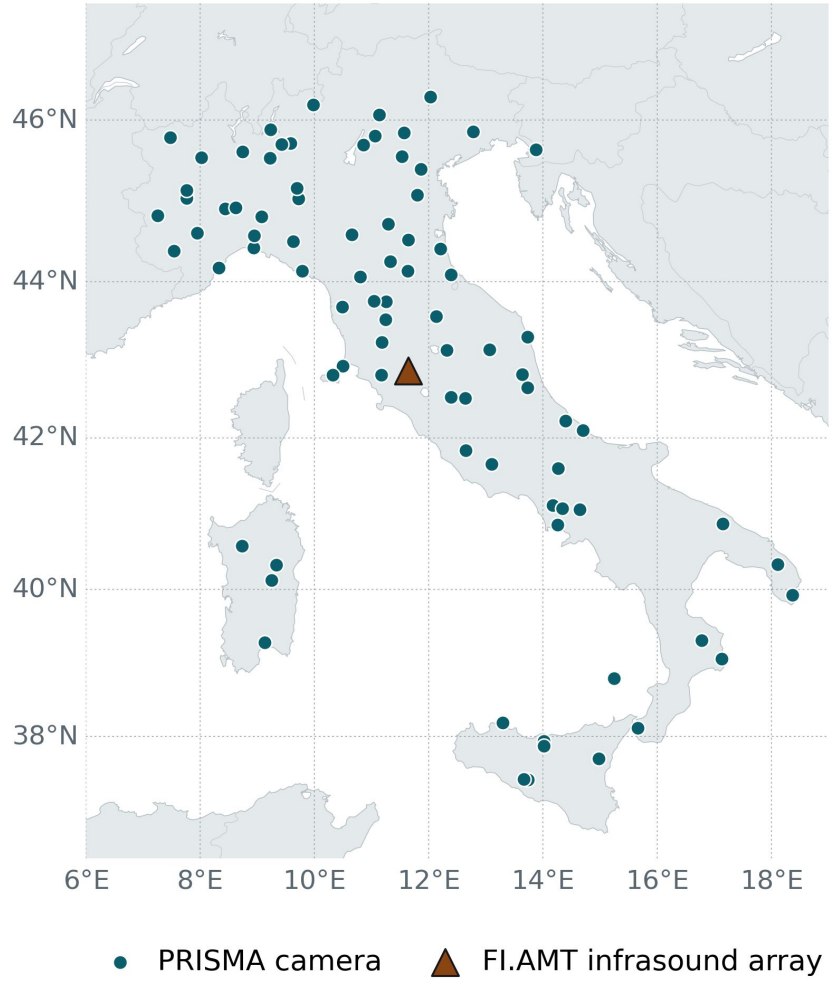
Infrasound can constrain energy and source altitude, after association

- In principle, the signal period constrains the energy, without the optical assumptions
- With ray tracing, it also narrows down where along the trail the signal came from
- Both hold only if the signal is reliably associated with the fireball
- **This association is the first step, and the subject of this talk**



FI.AMT infrasound record, 2021-10-01 (UT). Data: UniFI–DST (2024), via EIDA-INGV.

The data: PRISMA and the FI.AMT array



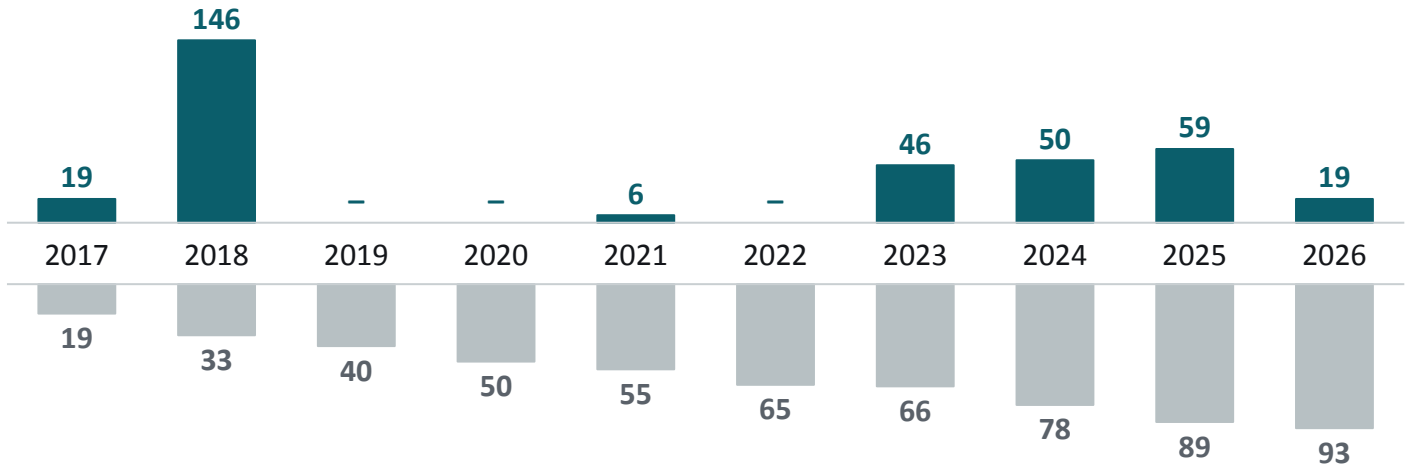
+ 10 cameras outside this view

From the archive (July 2026) to this study

~970	→	625	→	370	→	345
triangulated		Pass trajectory checks		with FI.AMT data		fireballs ray-traced

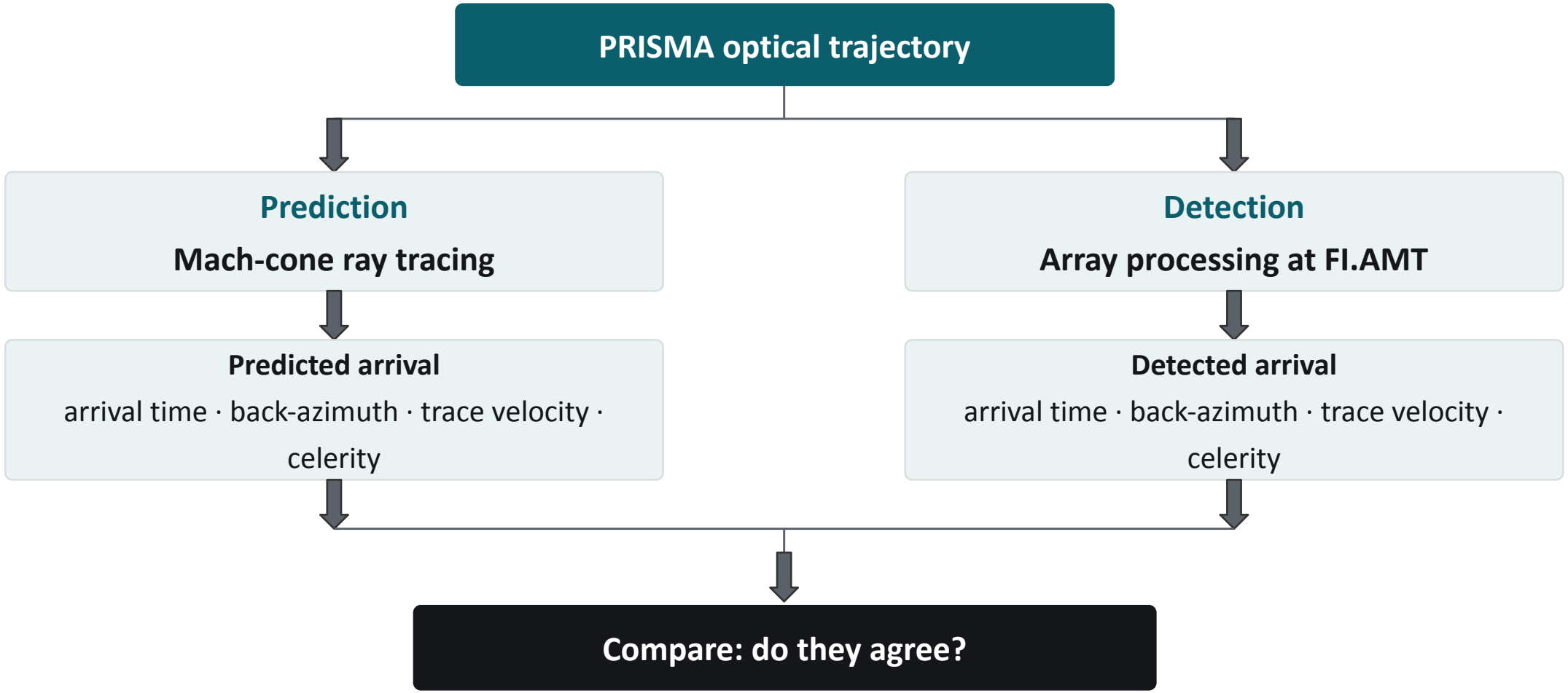
PRISMA archive event execution is in progress.

Fireballs in this study



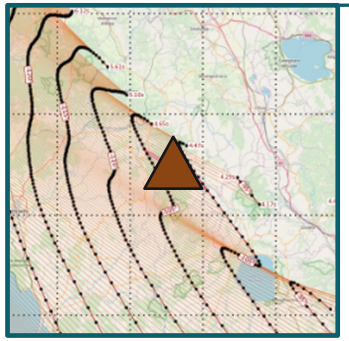
~ PRISMA cameras set up by 31 Dec (cumulative)

Two processing chains from one optical trajectory



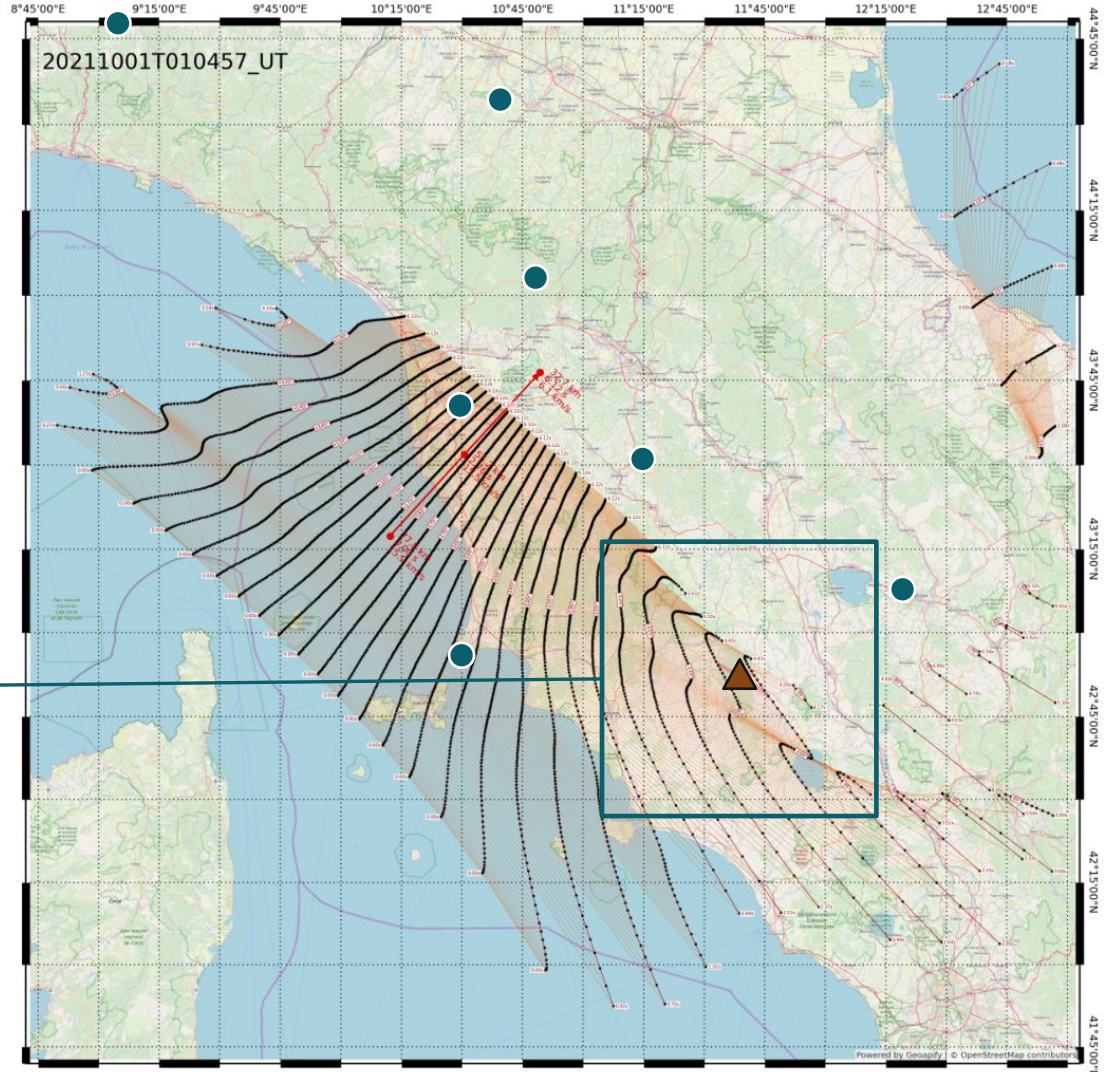
Prediction: ray tracing from the optical trajectory

1. We model the trajectory as a **supersonic line source**: at each trail point, rays leave perpendicular to the **Mach cone**.
2. Rays are traced with **infraGA/GeoAc** through the atmosphere of that hour (**NCPA Ground-to-Space**), which changes along the path.
3. Rays passing close to the array are **refined**; they give the **predicted arrival** and the loss along the path.



● PRISMA cameras that recorded this fireball (one more, Camerino, lies east of the map)

Zoom around FI.AMT

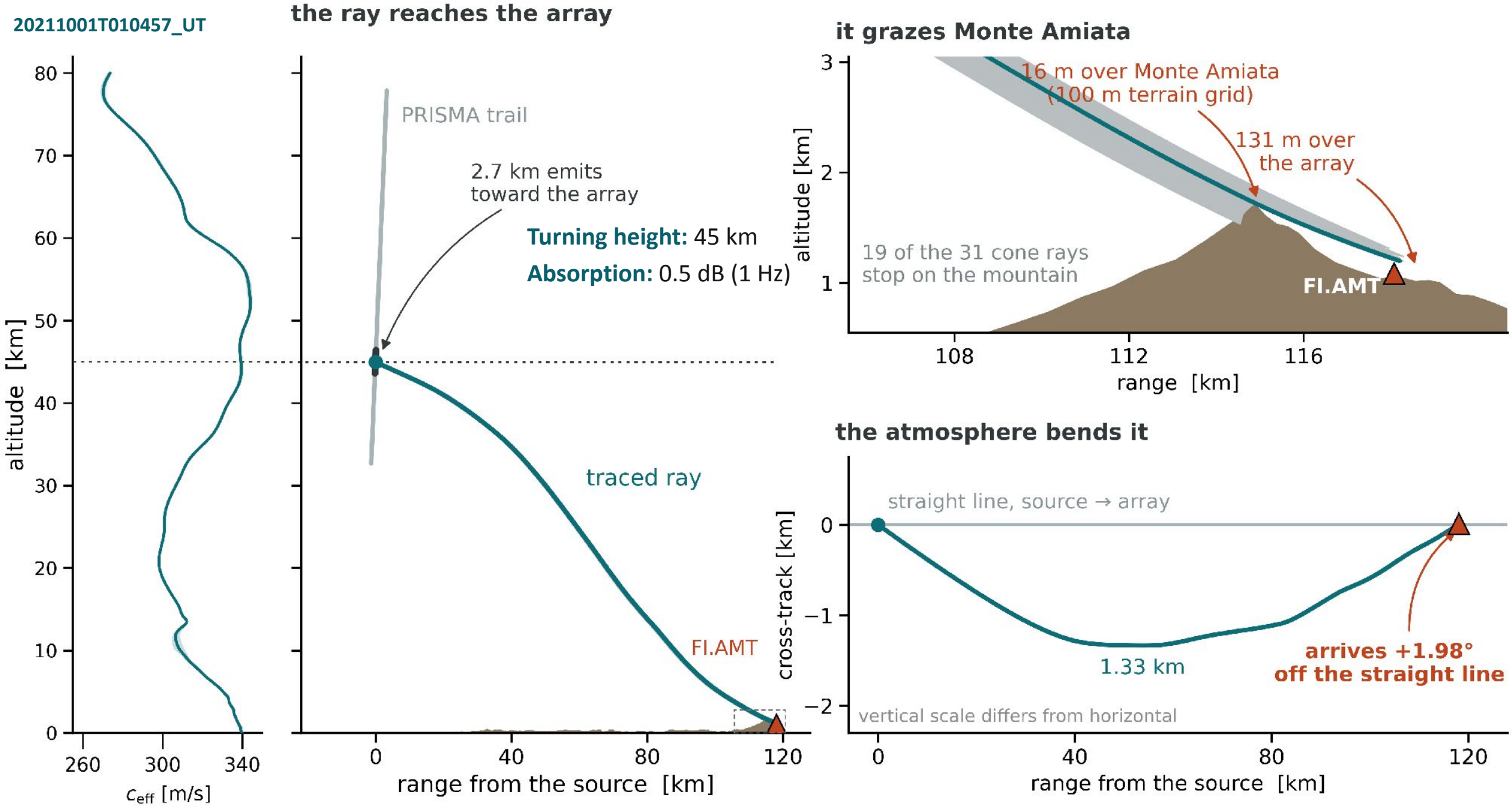


Where the Mach-cone rays reach the ground · 2021-10-01 fireball

infraGA/GeoAc: Blom et al. (2024), J. Acoust. Soc. Am. 155(3), 1667–1681

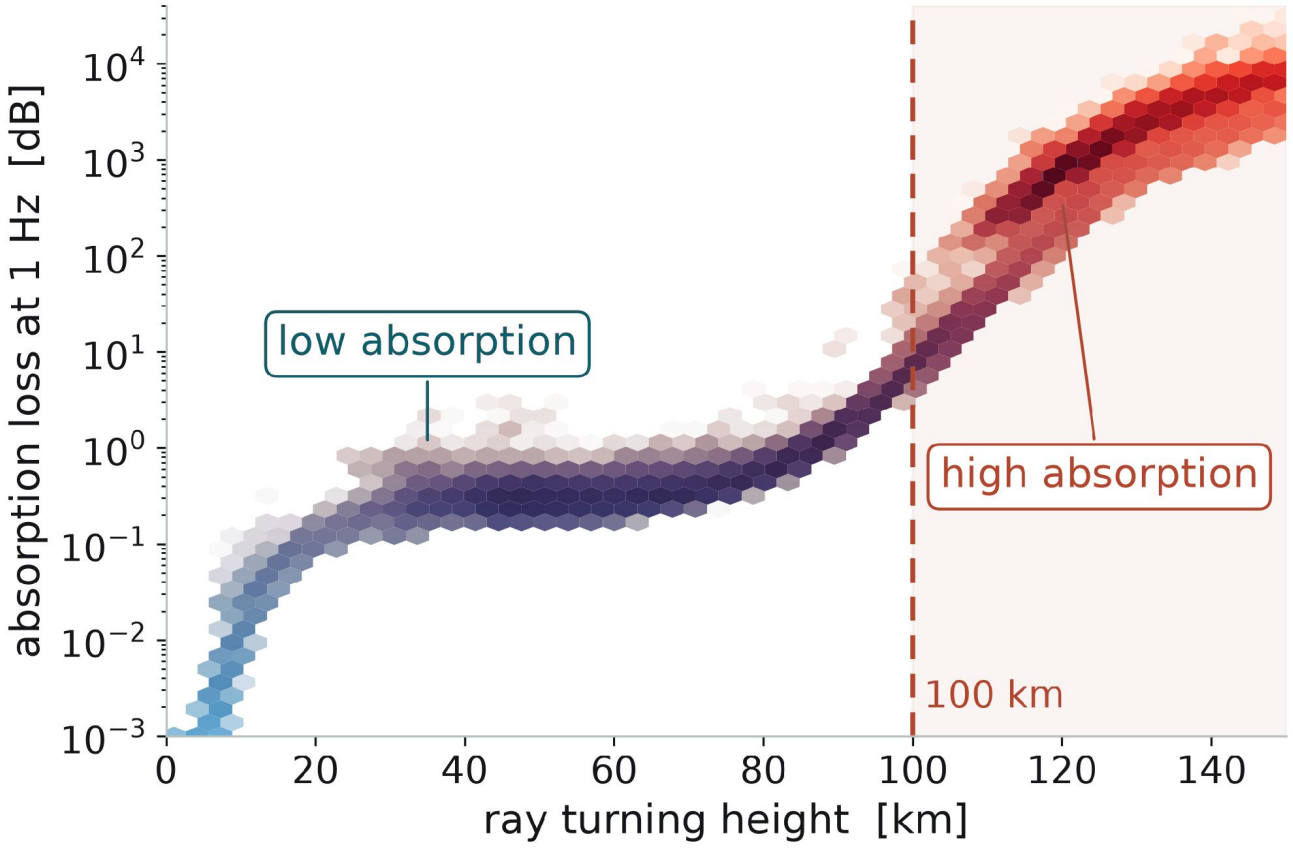
NCPA G2S: Hetzer (2024), The NCPAG2S command line client, doi:10.5281/zenodo.13345069

20211001T010457_UT



Terrain: TINITALY DEM — Tarquini et al. (2007), Ann. Geophys. 50, 407–425

Rays turning above 100 km are strongly absorbed

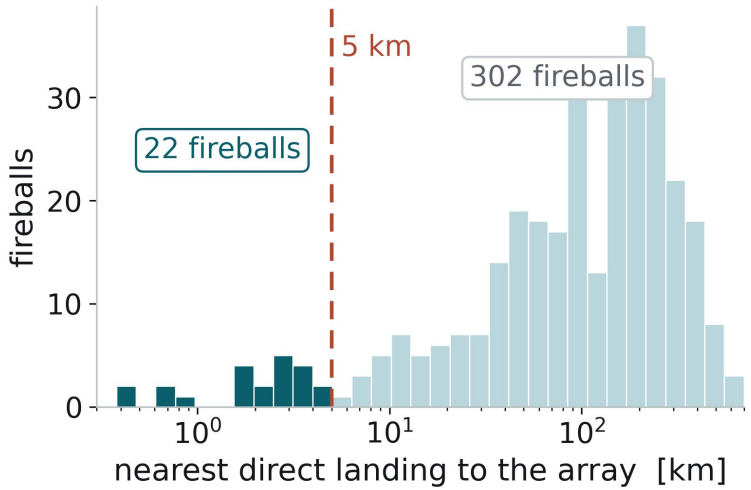


this work · 444 962 direct rays from 324 fireballs · Sutherland-Bass absorption at 1 Hz

- Rays that turn below about 90 km lose **about 1 dB or less**. Rays that turn above 100 km lose **tens to thousands of dB**.
- A ray can **land near the array and still be lost**, if it turned above 100 km on the way.
- At **0.5 Hz**, the lowest frequency we analyse, a ray turning above 100 km still loses **over 500 dB**.

Ray landings and fireball tracks

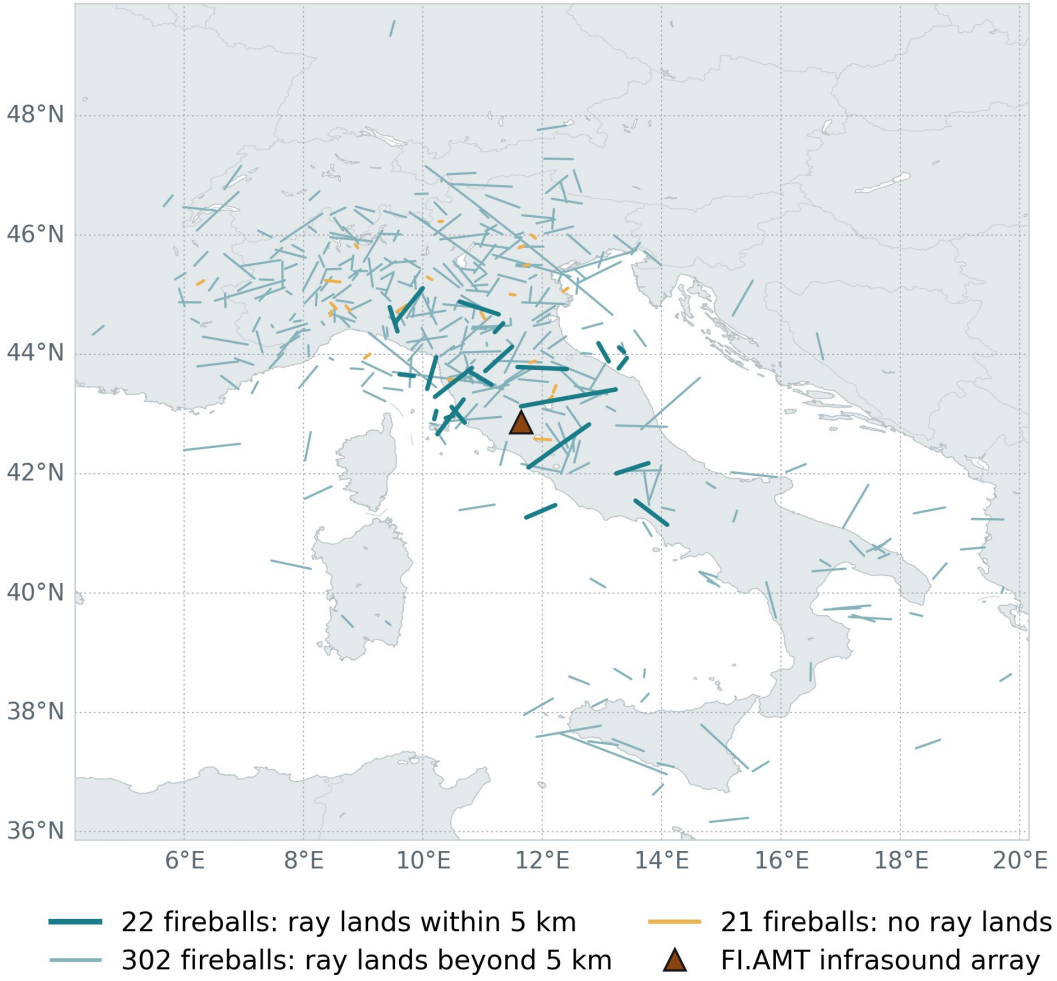
Ray landings relative to the array



- Only **22 land a direct ray within 5 km** of the array.

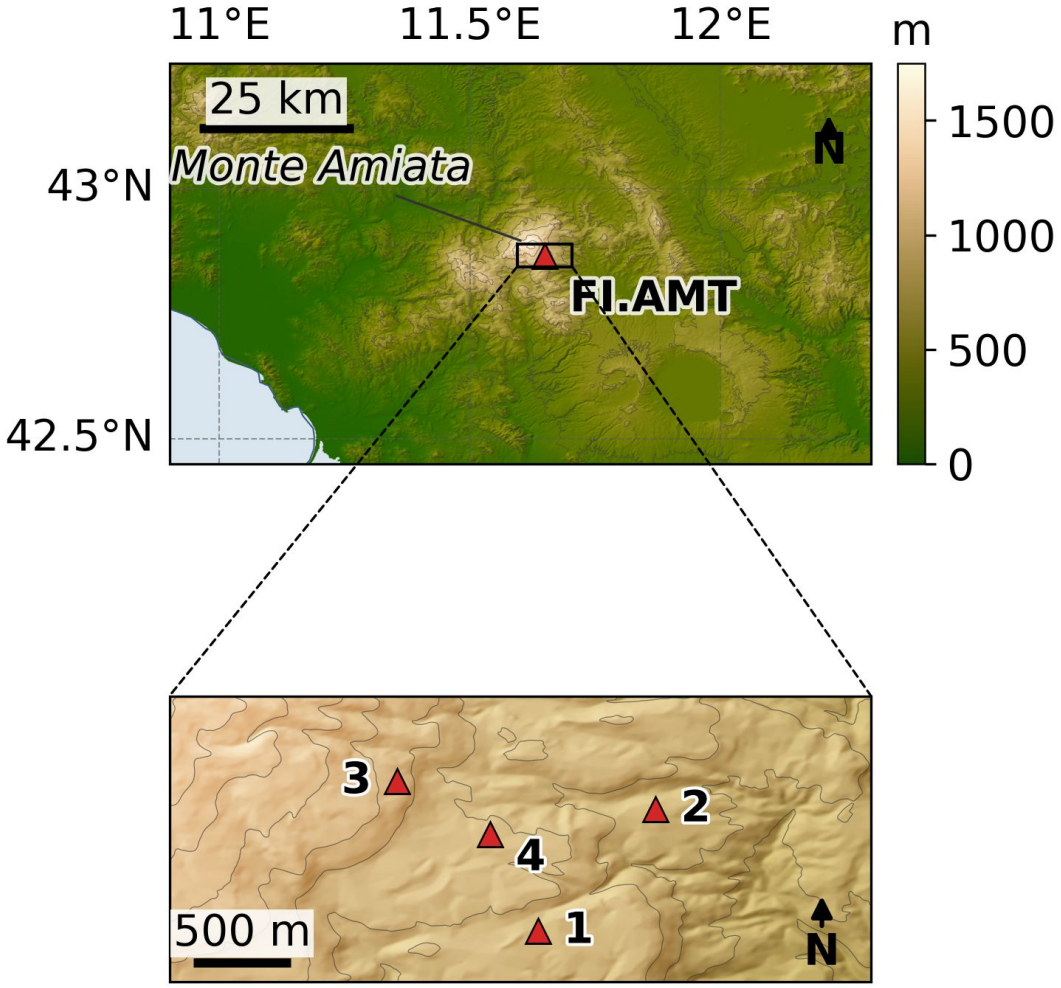
- After refining the rays, **21 have a predicted path** to the array.
- Fireballs passing **as close as 30 km** to the array can still land no ray near it.

Fireball ground tracks relative to the array



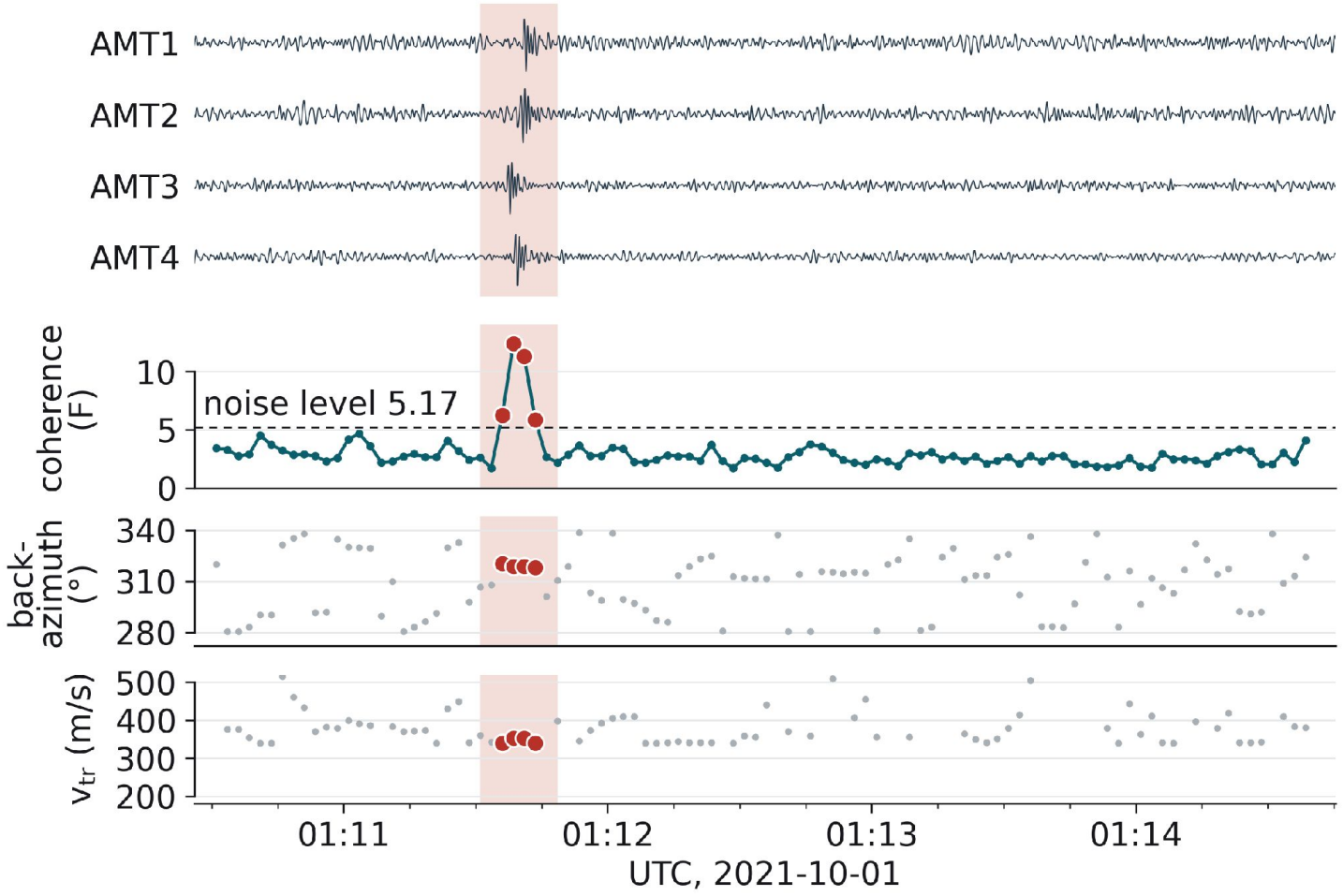
Detection: array processing at FI.AMT

1. **Four microbarometers** on Monte Amiata, recording all night
2. **Beamforming**: the delays between the four sensors give the direction of a signal, its trace velocity and its coherence (F)
3. **Kept if the four sensors see the same wave**: F above the noise level, and an acoustic trace velocity
4. **Kept if significant**: the other nights rarely give a peak this high
5. **Kept if it arrives in the time window** predicted from the trail, without the ray tracing



FI.AMT: UniFI–DST Seismo-acoustic Network [Dataset], INGV 2024, doi:10.13127/SD/0U-YV3X6DU
terrain: TINITALY 1.1 (INGV) · coastlines: Natural Earth

Detection: the 20211001T010457_UT fireball at FI.AMT



Detected arrival · 4 windows

arrival 01:11:38.5 UTC (peak window)

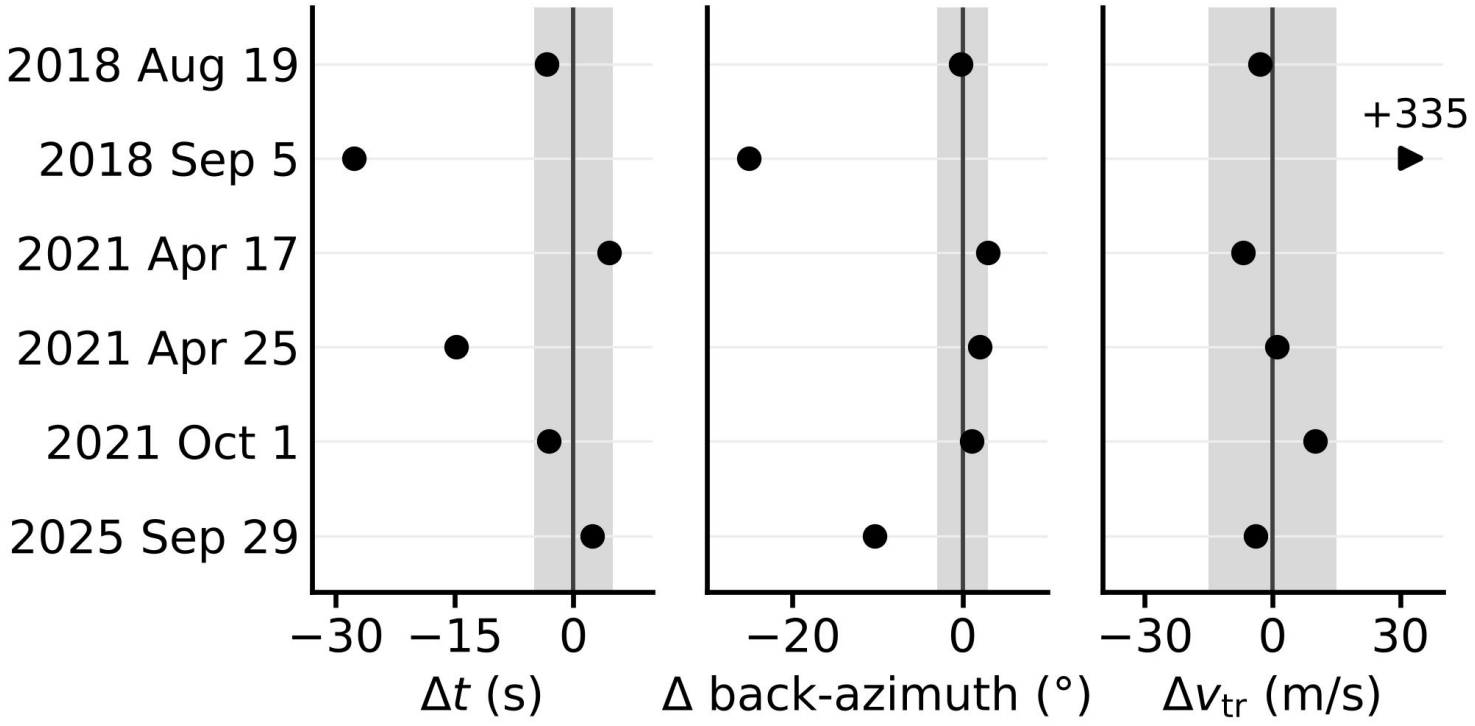
back-azimuth 319.0° ± 0.8°

trace velocity 340–353 m/s (search limit 340)

same wave: F 12.4, noise level 5.17

on time: inside the time window

Comparison: predicted and detected arrivals for 6 fireballs



1. **Arrival time**: 3 of 6 within 5 s
2. **Back-azimuth**: 4 of 6 within 3°
3. **Trace velocity**: 5 of 6 within 15 m/s
4. **Celerity**: 4 of 6 within 0.02 km/s

Comparison: where prediction and detection disagree

	Detected	Not detected
Ray path 21 fireballs	**6** **As predicted**	**15** 8 absorbed **7 unexplained**
No ray path 321 fireballs	**13** False detection, **or a missed path**	**308** **As predicted**

Possible reasons for the 7 and the 13 (untested)

- terrain in the ray refinement
- fragmentation source not modelled
- optical trajectory uncertainty

Conclusions and future work

Conclusions

- **Source–receiver geometry and the atmosphere play a major role** in detection; distance alone does not determine whether a ray reaches the array
- **Detected sound travelled directly down from the trail**; sound that had to turn high in the atmosphere was not detected
- **Ray-traced prediction is needed to interpret the recorded arrivals**
- **Most detections can be traced to a point on the trail**, through agreement with the ray (45–93 km)

Future work

- **Energy**: pair the measured period with the source altitude from the ray; test it on independent energies
- **Modelling**: add fragmentation sources, and carry trajectory and atmosphere uncertainties into the predictions
- **Archive**: confirmed meteor infrasound arrivals, and what separates detected from undetected fireballs

Thank you

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References, data and tools

Optical data: PRISMA fireball network

Infrasound data: UniFI–DST (2024), Seismo-acoustic Network of the University of Florence [Dataset], INGV, doi:10.13127/SD/0U-YV3X6DU

Waveform processing: ObsPy — Beyreuther et al. (2010), Seismol. Res. Lett. 81(3), 530–533, doi:10.1785/gssrl.81.3.530

Ray tracing: infraGA/GeoAc — Blom et al. (2024), J. Acoust. Soc. Am. 155(3), 1667–1681, doi:10.1121/10.0025025

Atmosphere: NCPA G2S — Hetzer (2024), The NCPAG2S command line client, doi:10.5281/zenodo.13345069

Period–yield relations: Silber et al. (2025), Astron. J. 170(1), 38, doi:10.3847/1538-3881/add47d

Terrain: TINITALY DEM — Tarquini et al. (2007), Ann. Geophys. 50, 407–425

Maps: Google Earth · coastlines: Natural Earth

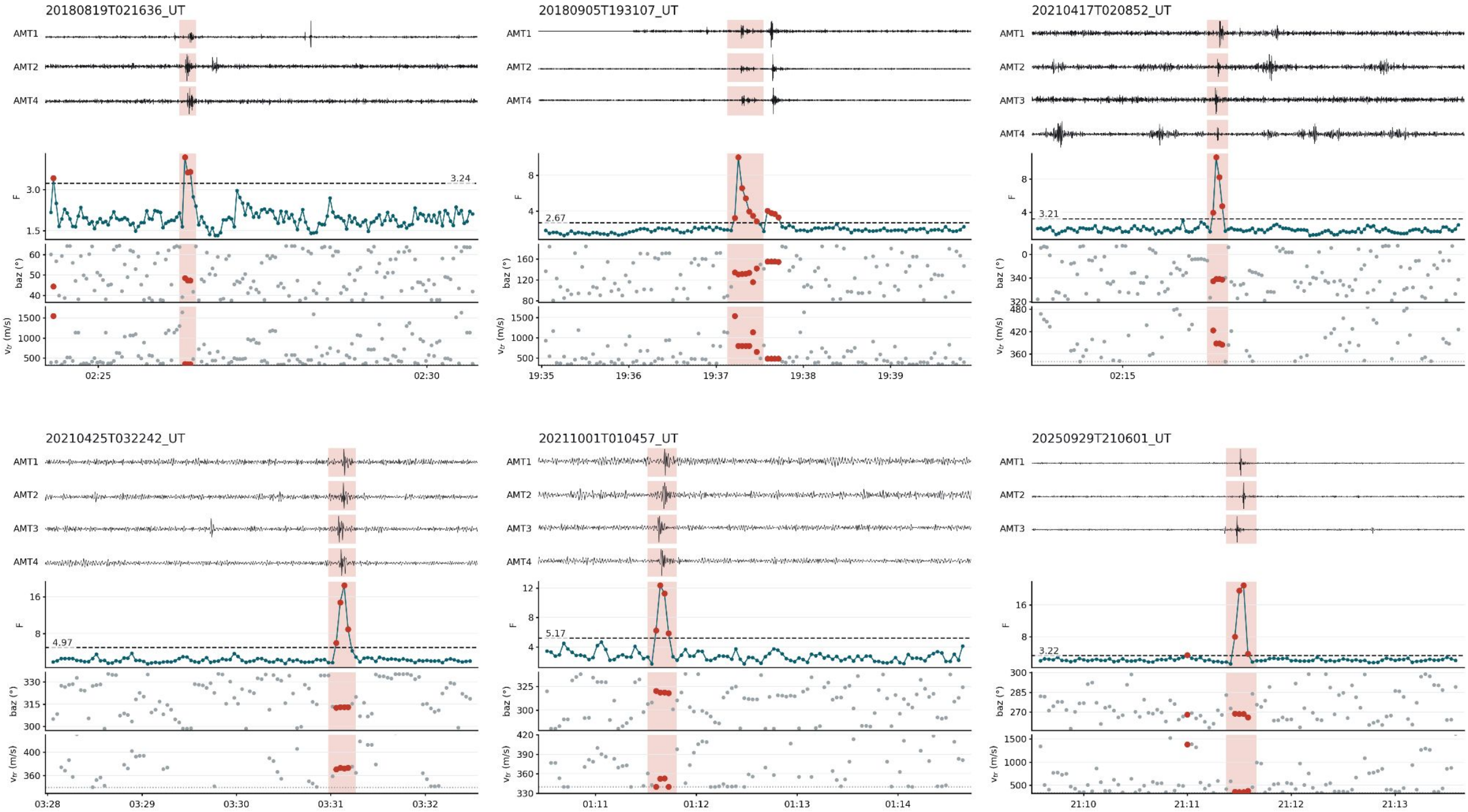
PRISMA DAY 2026

ROVERETO, ITALY

Backup: optical results for the 6 fireballs of slide 12

		height (km)		speed (km/s)		trajectory				brightness	
fireball	cameras	begin	end	initial	final	inclination (°)	azimuth from N (°)	length (km)	duration (s)	peak abs. magnitude	at height (km)
2018-08-19 02:16:36.65 UT	2	87.03 ± 0.05	63.26 ± 0.07	43 ± 1	39 ± 2	46.4 ± 0.1	209.4 ± 0.3	32.83 ± 0.05	0.80 ± 0.05	−6.46 ± 0.04	69.1
2018-09-05 19:31:06.70 UT	5	113.52 ± 0.05	86.8 ± 0.4	65.5 ± 0.2	62 ± 1	12.75 ± 0.09	46.08 ± 0.05	120.1 ± 0.2	1.90 ± 0.05	−7.20 ± 0.04	97.8
2021-04-17 02:08:52.78 UT	6	83.48 ± 0.01	53.75 ± 0.07	28.92 ± 0.07	17.1 ± 0.6	26.31 ± 0.05	218.44 ± 0.04	66.91 ± 0.07	2.44 ± 0.05	−4.62 ± 0.09	60.2
2021-04-25 03:22:41.95 UT	5	101.28 ± 0.02	81.66 ± 0.02	44.3 ± 0.7	43 ± 1	32.52 ± 0.05	72.50 ± 0.03	36.49 ± 0.03	0.84 ± 0.05	−3.87 ± 0.08	89.6
2021-10-01 **01:04:56.17 UT**	**8**	**79.46** **± 0.03**	**32.30** **± 0.09**	**16.21** **± 0.04**	**7.0** **± 0.1**	**32.1** **± 0.1**	**223.8** **± 0.1**	**88.51** **± 0.05**	**6.10** **± 0.05**	**−8.66** **± 0.04**	**40.3**
2025-09-29 21:06:00.70 UT	2	85.50 ± 0.06	30.61 ± 0.07	18.4 ± 0.1	4.7 ± 0.5	58.1 ± 0.2	148.7 ± 0.1	64.65 ± 0.08	4.00 ± 0.05	−7.88 ± 0.06	57.7

BACKUP


20180819T021636_UT
AMT1
AMT2
AMT4
F
3.24
baz (°)
v_{tr} (m/s)
02:25
02:30
20180905T193107_UT
AMT1
AMT2
AMT4
F
2.67
baz (°)
v_{tr} (m/s)
19:35
19:36
19:37
19:38
19:39
20210417T020852_UT
AMT1
AMT2
AMT3
AMT4
F
3.21
baz (°)
v_{tr} (m/s)
02:15
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AMT2
AMT3
AMT4
F
4.97
baz (°)
v_{tr} (m/s)
03:28
03:29
03:30
03:31
03:32
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AMT2
AMT3
AMT4
F
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v_{tr} (m/s)
01:11
01:12
01:13
01:14
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AMT2
AMT3
F
3.22
baz (°)
v_{tr} (m/s)
21:10
21:11
21:12
21:13